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RESEARCH and EXPERIMENTATION

Interconnection of the electricity and heating sectors to support the energy transition in cities

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ABSTRACT

The electricity, heating, and transport sectors in urban areas all have to contribute to meeting stringent climate targets. Cities will face a transition from fossil fuels to renewable sources, with electricity acting as a cross-sectorial energy carrier. Consequently, the electricity demand of cities is expected to rise, in a situation that will be exacerbated by ongoing urbanisation and city growth. As alternative to an expansion of the connection capacity to the national grid, local measures can be considered within city planning in order to utilize decentralised electricity generation, synergies between the heating and electricity sectors, and flexibility through energy storage technologies.

This work proposes an optimisation model that interconnects the electricity, heat, and transport sectors in cities. We analyse the investments in and operation of an urban energy system, using the City of Gothenburg as an example. We find that the availability of electricity from local solar PV together with thermal storage technologies increase the value of using power-to-heat technologies, such as heat pumps. High biomass prices together with strict climate targets enhance the importance of electricity in the district heating sector. A detailed understanding of the integration of local low-carbon energy technologies can give urban planners and other city stakeholders the opportunity to take an active role in the city's energy transition.

Keywords:

Urban energy planning;
Flexibility;
District heating;
Smart cities;
Photovoltaic;

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1. Introduction

The development and planning of cities in the 21st century face a number of challenges. Concomitant with managing continuous growth and urbanisation [1], cities must implement policies to meet climate targets and mitigate carbon emissions [2]. Energy planning in cities has to include and integrate efficiently the different sectors for electricity, mobility, heating and cooling, into what is often called "smart cities" [3,4]. Increased electrification is seen as one corner-stone of this development. New electricity loads, together with an increased population density, are likely to increase the annual and peak electricity demands of cities. As a consequence, several cities have identified an urgent need to increase the connection capacity from the national electricity grid. Investments in new capacity are often associated with long lead-times. An alternative, which is the focus of the present work, is to increase reliance on local electricity and heat generation, in combination with the utilisation of flexibility by storage technologies.

Sectorial couplings and electrification have, on larger geographical scales, been identified as important components of a fossil-free energy system [5,6]. How such couplings play out on a limited urban scale remains to be analysed in detail. The different parts of city energy systems are represented in the literature by, for example, the integration of a large share of renewables into the urban energy system [7–10], the integration of electric vehicle charging [11–13], the operation of urban district heating

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The North European Energy Perspectives (NEPP), a multidisciplinary project focusing on the development of local and national North European energy systems is funded by partners including energy companies, industry and the Swedish Energy Agency.
Local access of power has become a major challenge in parts of Sweden. Urbanisation, new construction and the transition from fossil fuel to electricity leads to growing electricity demand in cities. Part of the solution will be increased interaction between sectors and local production units, but many questions for city planning remain.
The model developed in this research provides an important tool to analyse the interconnection between the electricity, heat and transport sectors. The model and analysis of design and operation of a city´s energy system is crucial for local strategic planning and the possibility to reach climate targets. The stakeholders in NEPP will benefit from the result of the research.

Kjerstin Ludvig, Project management NEPP

systems [14–17], and sector-overlapping analyses [18–21]. Previous studies have provided valuable insights into low-carbon scenarios in different parts of the city energy system. The present work adds to this body of knowledge by including options for investments and dispatch of technology in relation to both the electricity and heating systems, as part of the techno-economic optimisation modelling. We model future, zero CO_2-emission energy systems in growing cities, with the focus on the interconnections between the electricity and heating sectors, while considering a fixed limit on hourly electricity import from the national grid.

This paper presents and applies a linear urban energy system optimisation model and analyses:

- The potential role of local energy balancing, i.e. local electricity and heat generation, together with electricity and thermal storage technologies; and
- Investments in and the composition of urban electricity and district heating systems, directed towards meeting stringent CO_2 emission targets.

The model is applied using the city of Gothenburg as a case study. Similar to other cities, for example Copenhagen [22], the city of Gothenburg has formulated strategies to reduce its climate impact, by aiming to e.g. phase out fossil fuels in the district heating system, produce 500 GWh of renewable electricity and reduce CO_2 emissions from road transport by 80% as compared to 2010, all by 2030 [23].

The paper is organised as follows. Section 2 describes the flexibility potential of sectorial coupling in an urban energy system and the method developed. Section 3 gives the results from the modelling of an example city. Section 4 presents a discussion of the assumptions made in the modelling. Section 5 presents the conclusions drawn and reflections as to further developments to the proposed model.

2. Method

This work represents a part of the development of a linear energy system optimization model for cities, which includes investments as well as the dispatch of energy technologies with hourly time resolution, herein applied to the city of Gothenburg, Sweden. Figure 1 presents the different modules of the city optimization model. The objective of the model is to minimize the total operational and investment costs in the electricity and heating sectors, while complying with a constraint on CO_2 emissions. A full description of the model used in this study is provided online in the Appendix A.

In the model, the hourly electricity load profile can be met by a combination of electricity that is imported from the national electricity grid to the city, electricity that is generated within the city borders and electricity that is discharged from an electricity storage. The amount of electricity that can be imported is limited by the import capacity. To focus the analysis on the effect of local generation and storage technologies on system design and operation, no export from the city energy system to the national grid is considered in the current version of the model. The hourly district heating demand cannot be met by heat delivered from outside of the city but has to rely on local heat production within the urban district heating system or the heat discharged from thermal storage units.

The electricity and district heating demand profiles are used as inputs to the model, together with a

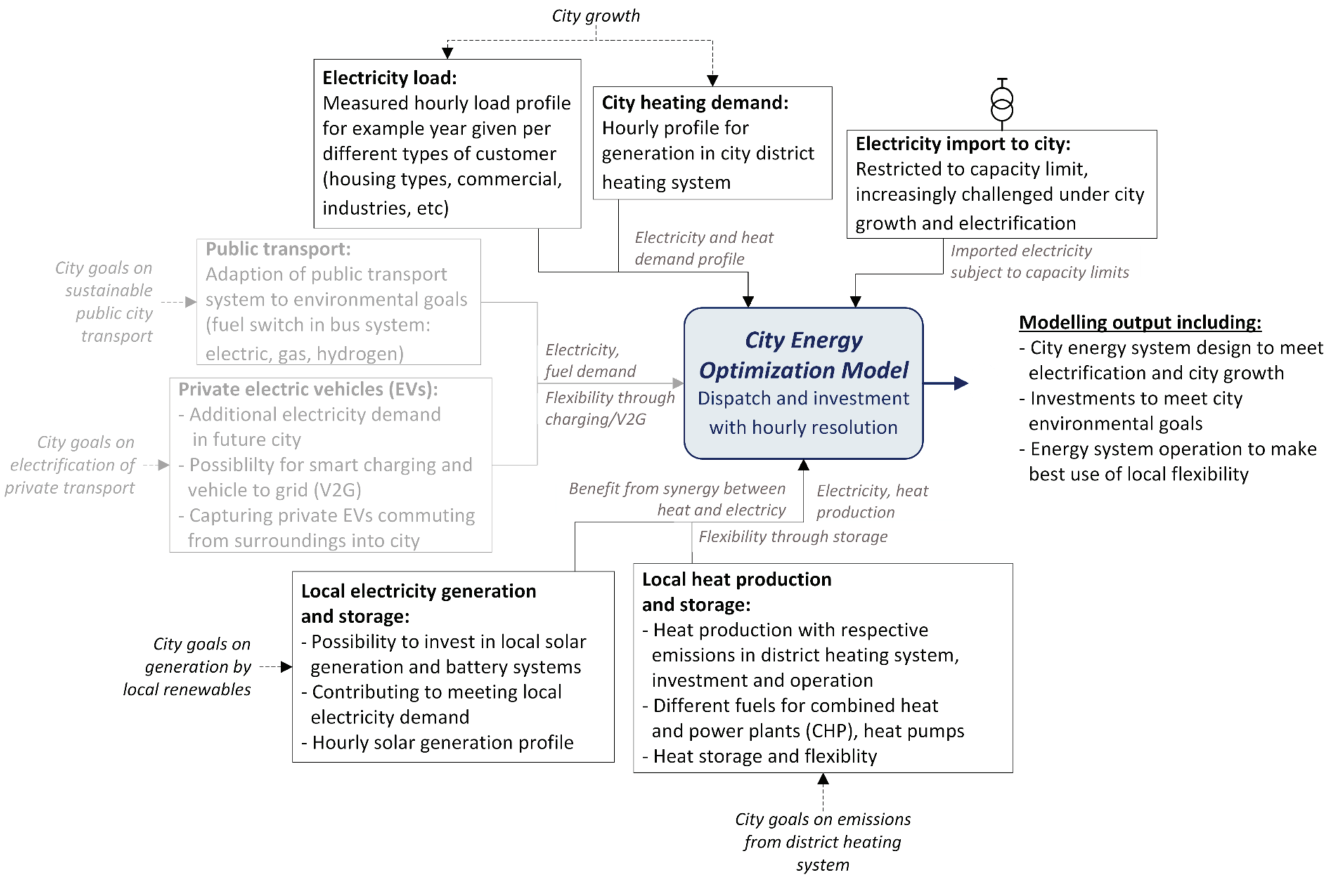

Figure 1: Schematic of the City Energy Optimisation Model with its inputs (squared boxes) and outputs, where inputs are specified for the electricity, heat, and transport sectors. The shaded boxes are modules that are under development and will be addressed in future studies

description of the existing electricity and heat generation units presently available in the City of Gothenburg. Thus, new investments in heat generation and storage technologies are made by the model for replacing fossil-fuelled technologies and to cover the increased demand for heat. New electricity generation and storage capacity are invested in when competitive compared to importing electricity from the national grid or if the import capacity cannot meet demand in the city. The model minimises the total cost to supply electricity and heating demand for 1 year, i.e., the investment and operational costs for electricity, heating, and storage technologies with a constraint on CO_2 emissions.

The modelling includes the following technology options:

- *Electricity generation:* Solar PV technologies, peak power gas turbines fired by natural gas or biogas.
- *Electricity storage:* Li-Ion batteries, flow batteries.
- *Combined heat and power (CHP):* CHP fired by biomass (wood chips), waste, natural gas or biogas.
- *Heat production:* Heat-only boilers (HOB) fired by biomass, natural gas, biogas, waste or oil, heat pumps, electric boilers, industrial excess heat.
- *Thermal storage:* Tank storage, pit storage, borehole storage.

Details of the current heat and power system and the costs and technical assumptions associated with the investments options are given online in Appendix B. The electric vehicle and public transport modules of the optimisation model, shown in grey in Figure 1, are not part of the results presented in this work, which focuses on the interconnections between the electricity and heating sectors, including the use of heat and electricity storage units. The synergies between electric vehicle charging and discharging and the city electricity and heating sectors will be investigated in a future study.

2.1. Flexibility and synergies in the electricity and district heating sector

Figure 2a shows the hourly profiles of electricity and heat demand for the City of Gothenburg, used as inputs to the model. It is clear that there are pronounced seasonal variations, as well as variations on the weekly, diurnal and hourly levels. The model applies the above mentioned technology options to supply the district heat demand and electricity for the city demand. Heat generation technologies include electricity-dependent options, such as heat pumps. In addition, the model includes storage options for both heat (within the district heating system) and electricity (battery technologies). Thus, the model can evaluate the potential for flexibility and the linkages between electricity and district heating. The hourly electricity price, as utilized for electricity imported to the city energy system in the modelling is presented in Figure 2b, with details on input data given in the Appendix online.

2.2. Cases and input assumptions

Table 1 provides a summary of the input data that describe the energy system for the City of Gothenburg and the common assumptions made to represent its future development, i.e., assumptions that remain the same in all the modelled cases. Thus, in the modelled cases Gothenburg is assumed to have increased electricity and heat demand by a factor of 1.5. Yet, in the model the connection capacity from the national grid to the city is limited to present day levels. This means that in modelled future cases the connection capacity limit corresponds to 55% of the maximum winter electricity load; and that there is sufficient connection capacity to cover all load by imported electricity during about 4 000 hours per year. In short, we model increasing demand in a city that is assumed to grow in size and population, however, without any possibility of new investments in connection capacity to the national grid. With these assumptions, we investigate the roles of local generation and flexibility in the city energy system.

For the case study of the city of Gothenburg we investigate two base modelling cases and three additional modelling cases in a sensitivity analysis. The cases differ in terms of the cost assumptions for biomass (and biogas), PV, and batteries, as presented in Table 2. The *Low Cost Bio* case is intended to reflect the cost assumptions for a near-term future, while the *Low Cost PV* case should represent a longer-term future, with greater competition for biomass. The trajectories of the PV and battery investment costs and biomass prices are uncertain. To specify

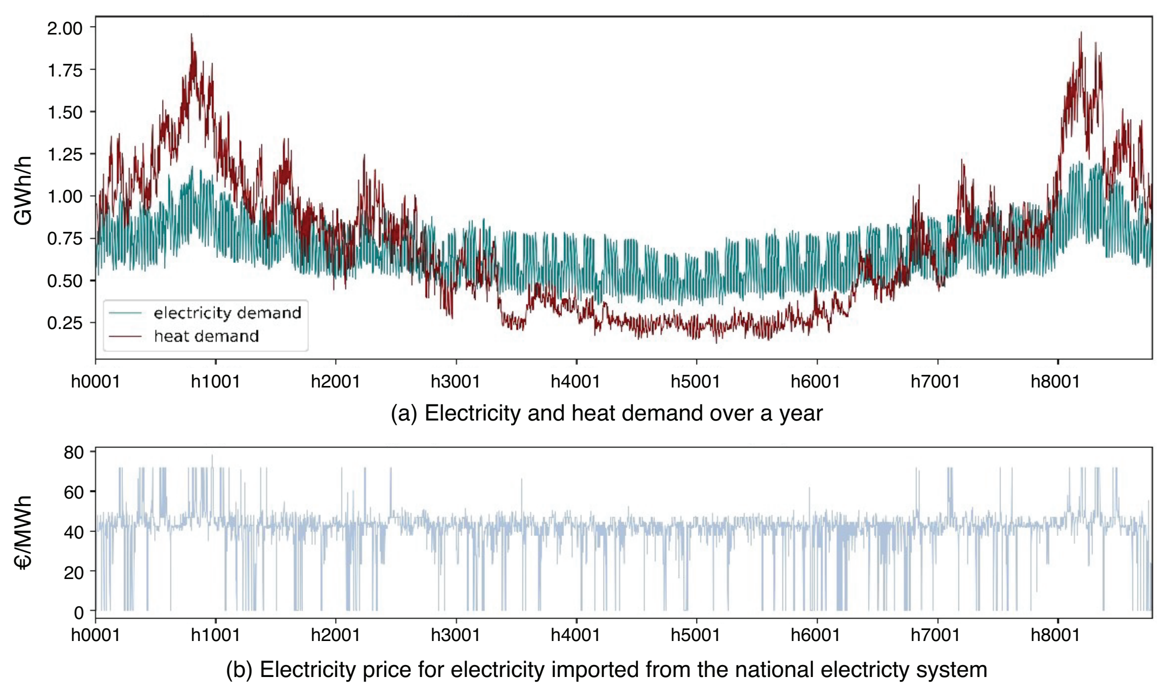

Figure 2: (a) Hourly electricity and district heating demand profile obtained for the City of Gothenburg, (b) Electricity price for electricity imported from the national electricity system, both as used in the modelling

Table 1: Input data used to describe the energy system of Gothenburg and assumptions made in modelling its future development (common to all the modelled cases)

Input data on the energy system	
Electricity and heat demand profile (hourly)	Actual profile for Year 2012
Connection capacity to the national system	As currently (2019) in place
Heat and electricity generation capacity in place (*cf.* Appendix B)	As of Year 2019, this considers the fuels used to run these processes and whether they are in line with the emissions constraint
Common assumptions for all cases:	
Demand growth	Both, the electricity and heat demand are assumed to increase by a factor of 1.5
Emissions targets	Zero emissions (not considering the emissions related to the electricity imported from the national grid)
Electricity price for imported electricity	Hourly price curve, as taken from the results of a Northern European dispatch model (for a future with an increased share of electricity generation from variable renewables) [24]

Table 2: Overview of the modelled cases and case-specific assumptions related to PV and battery investment costs and biomass fuel costs

	PV costs [€/kWp]	Biomass fuel costs [€/MWh][a]	Battery costs [€/kWh]
Base Cases:			
Low Cost Bio	600	20	150
Low Cost PV	300	40	150
Sensitivity analysis:			
Higher Cost Battery	600	20	300
Higher Cost PV	600	40	150
Low Cost PV, Low Cost Battery	300	40	70

[a] Biogas prices are calculated from biomass prices

the influences of technology and fuel cost assumptions in future years, we chose to assume the same level of city growth and a zero CO_2 emission target for all the cases. For each case, the optimisation modelling is run separately, and the results are compared in the analysis. A discount rate of 5% has been assumed for all model runs.

3. Results

3.1. Development of the city district heating and electricity sector

Owing to the constraints imposed on emissions from fossil fuel-fired technologies, the model phases-out approximately 300 MW of CHP capacity and 570 MW of HOB capacity, currently run on fossil fuels, mainly natural gas. In neither the *Low Cost Bio* case nor the *Low Cost PV* case, phased-out capacity is replaced with the same amount of CHP and HOB capacity compared to present levels. The future technology mix consists of less CHP and HOB capacities that are run on biomass fuels, and investments in solar PV, biogas turbines, electric HOB capacities and electricity and thermal storage units. Lower total capacity is required, because storage systems enable a more flexible utilization of the installed capacities and smoothening of the loads.

Figure 3 shows the dispatch of the generation and storage portfolio over a whole year for the *Low Cost Bio* case. It is evident that peak technologies, i.e. biogas-fired gas turbines for electricity and HOBs for heat, are used during the winter months. CHP fired by biomass is, however, operated also in the summer months, albeit at a reduced output. This is despite lower electricity and heat demands and higher level of electricity generation from solar PV during the summer months. The operation of the biomass CHP generation over different periods in the summer correlates well with the amount of thermal energy stored in the pit storage. In other words, a higher level of generation from CHP during the summer often increases the storage level in the pit storage. The waste heat production from industry is relatively constant over

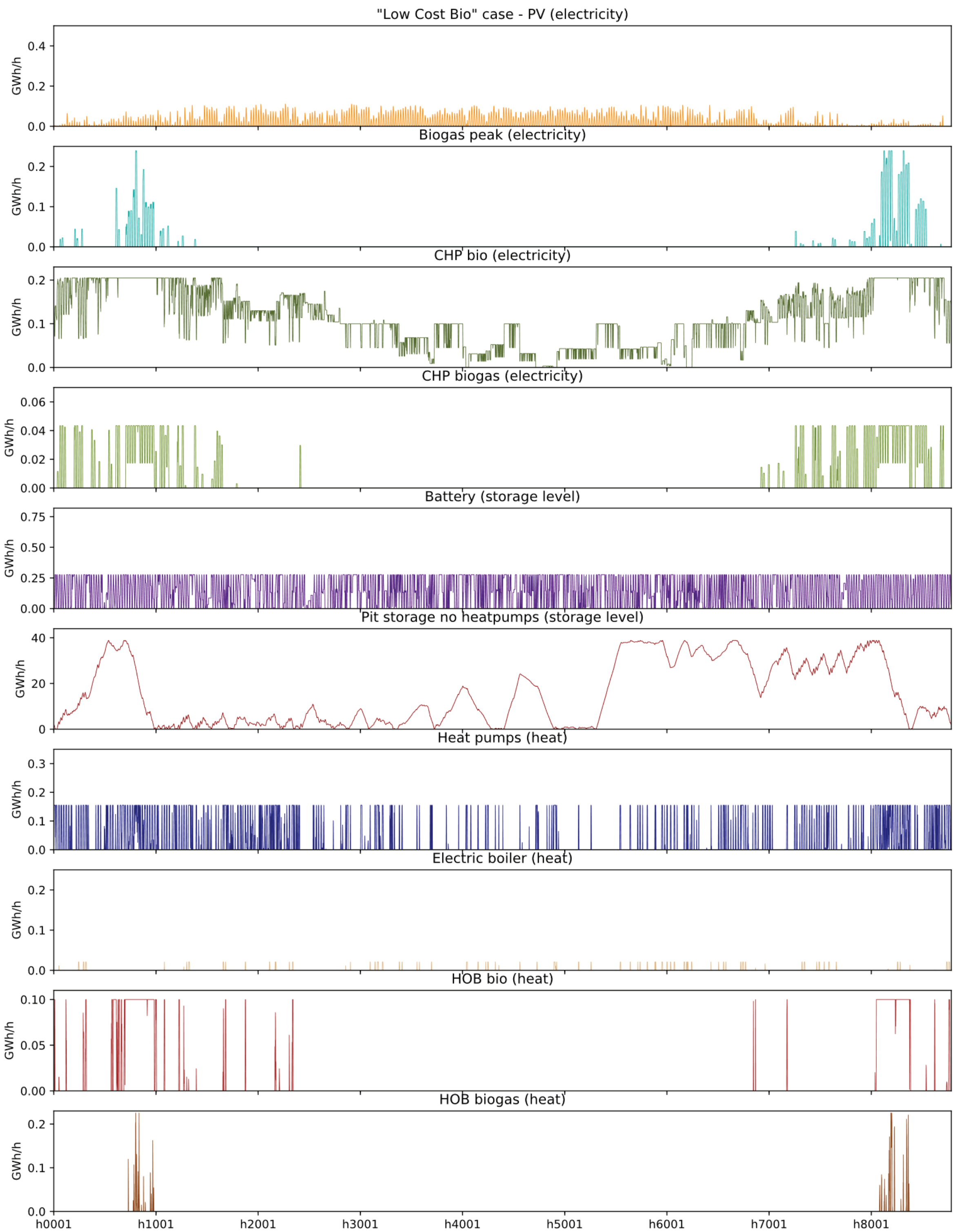

Figure 3: Dispatches of the different technologies for an entire year in the Low Cost Bio case, as obtained from the modelling. For electricity generation technologies, the electricity output is plotted, whereas for heat production technologies, the heat output is plotted. The power-to-heat ratios of 0.3 for biomass and 1.6 for biogas CHP plants explain the corresponding heat production levels from the CHP units. Observe that the scale for PV generation differs from the one in Figure 4, for better readability

the summer months. We have also found that CHP generation is reduced during hours of low electricity prices when more electricity is imported into the city and heat pumps and electric boilers are used to provide heat. The possibility to utilise thermal pit storage to supply heat during periods of highest heat demand can be assumed to dampen HOB investment and generation in this modelled case.

Figure 4 shows the dispatch of the different technologies for the *Low Cost PV* case. The biggest differences in relation to the *Low Cost Bio* case are the much larger investments in solar PV (due to the lower PV investment costs), as well as the investment in additional thermal storage capacity. The excess electricity from PV is stored either in batteries or as heat, mostly in long term pit storage. Thus, thermal pit storage with heat pumps is utilised as seasonal storage, as shown in Figure 4, whereby the storage level is at its lowest in the middle of April and peaks during September. It is also evident that biomass CHP is utilised to a lesser extent, especially during the summer months when CHP is not in operation. The large PV capacity, together with electricity imports and storage options are sufficient to supply the summer electricity load. The utilisation of heat pumps in the *Low Cost PV* case is more related to the PV generation profile than to the electricity price. It should be kept in mind that in the cases modelled, export of excess electricity from local generation in the city is not possible. Thus, heat pumps, especially during summer, are run to make use of PV-generated electricity, supply the heat load, and charge the thermal storage. Moreover, as a consequence of the high level of generation from PV, there are many more hours without electricity imports (especially in the day-time) in the *Low Cost PV* case, as compared to the Low Cost Bio case.

3.2. Synergies between the urban electricity and heat sectors

The *Low Cost PV* case, which combines lower PV costs with higher prices for biomass, shows a clear relationship between the electricity and heating sectors. Especially during summer, electricity is utilised for heat production, which is then combined with thermal seasonal storage. Pit storage systems with heat pumps have low constant losses and are therefore suitable for long-term storage. Tank storage in the *Low Cost PV* case takes on a role somewhat intermediate, in terms of storage duration, compared to the roles of battery storage (which stores electricity for usually not longer than a day) and pit storage. The time between charging and discharging of the tank storage units here varies from several hours up to several days.

3.3. Sensitivity analysis: Impact of PV and battery prices

The *Higher Cost PV* case, obviously, leads to a lower PV capacity compared to the *Low Cost PV* case, although it is still clearly higher than in the *Low Cost Bio* case. The 721 MW of PV capacity (almost 80% of the summer peak electricity load) that results from investment in the Higher Cost PV case is sufficient to avoid having to use wood chips CHP during the summer (biomass is an expensive fuel in both the *Low Cost PV* and the *Higher Costs PV* cases). Applying an assumption of a higher battery price of 300 €/kWh (as opposed to the 150 €/kWh price used in the base cases) exerts a weak impact on the results. Yet, the availability of cheaper batteries (at 70 €/kWh) in the *Low Cost PV, Low Cost Battery* case increases investments in PV and battery capacities, while reducing investment in biogas-fired peak units and heat pumps.

4. Discussion

In this work, a simplified growth factor of 1.5 for both the electricity and heat sectors in the city energy system has been applied to all the cases modelled. Yet, the development of future electricity and heating loads is highly uncertain. Energy efficiency measures on the electricity or heating side, the implementation of demand-side management and the utilisation of the building shell for thermal storage could influence the shapes of the demand profiles for electricity and heating. Considering any of the above measures in the analysis could flatten some of the demand peaks and thereby reduce the utilization of batteries and tank storage units, as compared to the results presented in this work. The magnitude of demand growth in the city's electricity and heating sectors over the upcoming decades depends largely on how the city continues to grow. New construction projects in cities often include low-energy buildings. At the same time, new, large-scale consumers (such as those arising from the electrification of industrial or manufacturing sites) could emerge.

The availability of sustainably harvested biomass in future scenarios and the assumed costs for this fuel are highly uncertain. Larger competition for biomass can be expected in future energy systems, raising the question

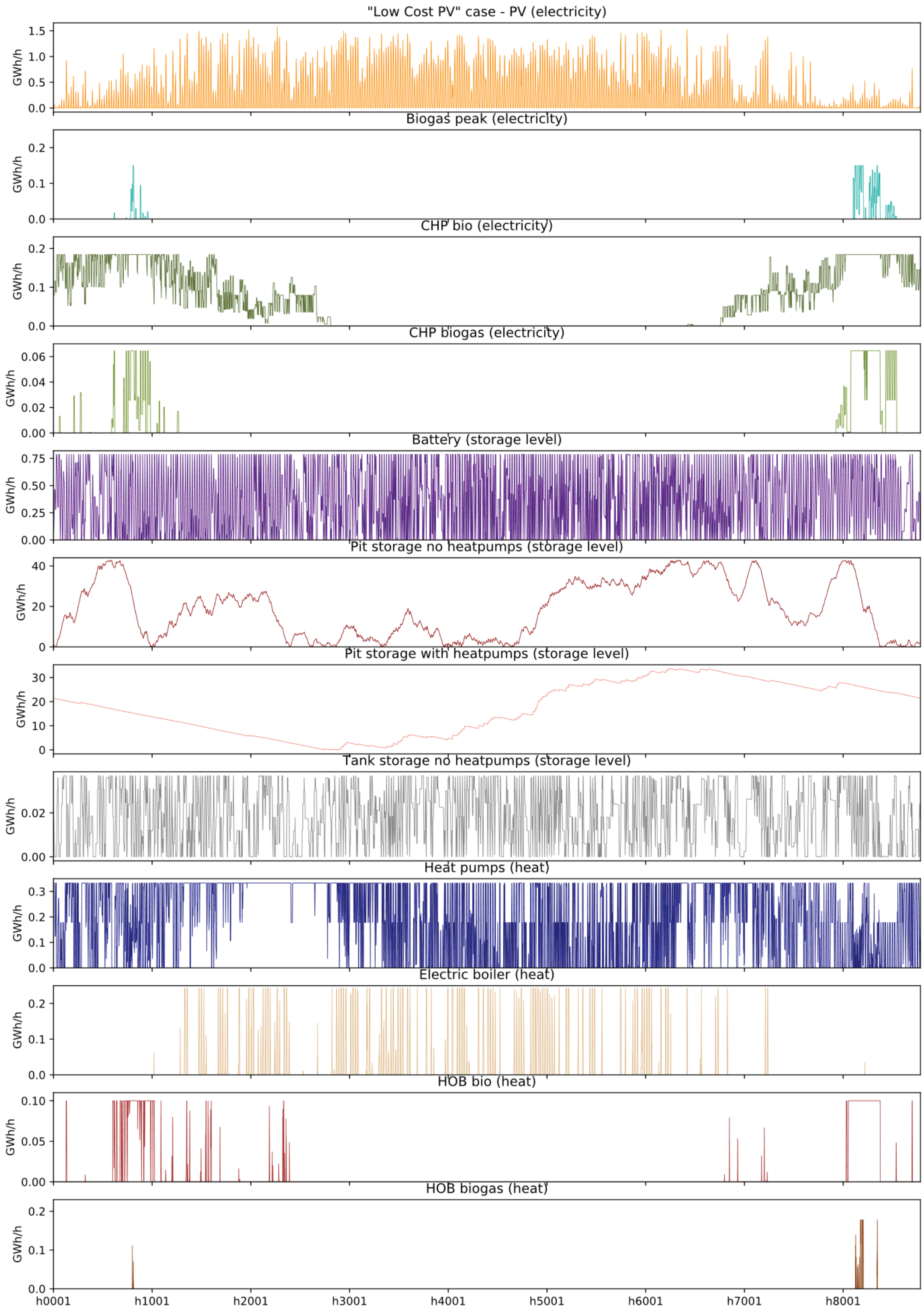

Figure 4: Dispatches of the different technologies for an entire year in the Low Cost PV case, as obtained from the modelling. For electricity generation technologies, the electricity output is plotted, whereas for heat production technologies, the heat output is plotted. The power-to-heat ratios of 0.3 for biomass and 1.6 for biogas CHP plants explain the corresponding heat production levels from the CHP units

whether the urban energy system is the best option to utilize this scarce resource in, or whether there are other sectors or other regions in the world with less alternatives to biomass that should be prioritized.

The sectoral integration in the city energy system involves the collaboration of a number of actors and stakeholders that traditionally did not develop common strategies. One aspect that can facilitate installation and operation of local energy technologies are local prices for electricity and heat. In a city where electricity import capacity is at its limits (as with the assumptions in the case study modelled) there should be an increased value of local generation of electricity to the urban energy system. If this value is also seen by local actors, through e.g. local prices or local markets for energy, an incentive is created for local energy generation and storage. Another option to foster a common organization of the city energy transition is the formulation of energy and climate goals and regulations imposed on urban actors to meet these. With an increased interest of private actors, like household customers, in owning small-scale generation and storage units parts of the investment in local technologies could be driven by small-scale actors. The EU's "The clean energy for all Europeans package" [25] enables active energy citizens and communities to be part of energy markets and thereby support the energy transition.

5. Conclusions and further work

Local integration of the electricity and heating sectors in the city energy system presents, to some extent, a viable alternative to expansion of the connection capacity to the national grid for growing cities. Thus, local balancing can make it possible for local stakeholders to address the issues of increasing energy/capacity demand and carbon-neutral energy supply and at the same time avoid costs and long lead times associated with new power lines and transformer stations. This work, which is based on a model developed to analyse the operation of integrated electricity and heating sectors in a smart city, evaluates two main cases with price assumptions on solar PV and biomass fuels using the City of Gothenburg as an example: a) A near-term future case, including low biomass fuel prices and higher PV investment costs, and b) a more-distant future case with higher biomass price and lower PV investment cost.

The results show that low-cost electricity within the city (here in the form of PV, assuming a further decrease in investment costs) is not only valuable in terms of the city's electricity system, but also with respect to providing heat through power-to-heat technologies. This is especially the case when there is a high cost for biomass. Thermal and electricity storage systems that shift energy over hours, days or even seasons become an important part of the city's energy system mix in all the cases investigated, especially when electricity from solar PV is available in abundance.

Future work will present an in-depth analysis of the impacts of electric vehicle charging and vehicle to grid discharging on the investments in and operation of electricity and heating technologies. Scenarios that involve other energy carriers, such as hydrogen could also be investigated. Public transport, in the form of busses run on electricity, hydrogen or biogas, can enrich the description of the transport sector in the urban energy system model.

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Appendix/Supplementary material:

Details on the mathematical model formulation and important input data is found online under http://dx.doi.org/10.5278/ijsepm.3328

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